

A strong radio brightening at the jet base of M87 in the period of the elevated TeV γ -ray state in 2012

K. Hada^{a,b}, M. Giroletti^a, M. Kino^{c,d}, G. Giovannini^{a,e}, F. D'Ammando^a, C. C. Cheung^f, M. Beilicke^g, H. Nagai^h, A. Doi^d, K. Akiyama^{b,i}, M. Honma^{b,j}, K. Niinuma^k, C. Casadio^l, M. Orienti^a, H. Krawczynski⁷, J. L. Gómez^l, S. Sawada-Satoh^b, S. Koyama^{b,d,i}, A. Cesarini^m, S. Nakaharaⁿ and M. A. Gurwell^o

^aINAF Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy

^bMizusawa VLBI Observatory, National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan

^cKorea Astronomy and Space Science Institute, 776 Daedukdae-ro, Yusong, Daejeon 305-348, Korea

^dInstitute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagami-hara 252-5210, Japan

^eDipartimento di Fisica e Astronomia, Università di Bologna, via Ranzani 1, I-40127 Bologna, Italy

^fSpace Science Division, Naval Research Laboratory, Washington, DC 20375, USA

^gPhysics Department and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130, USA

^hNational Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan

ⁱDepartment of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

^jDepartment of Astronomical Science, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

^kGraduate School of Science and Engineering, Yamaguchi University, 1677-1 Yoshida, Yamaguchi, 753-8512, Japan

^lInstituto de Astrofísica de Andalucía, CSIC, Apartado 3004, 18080 Granada, Spain

^mDepartment of Physics, University of Trento, I38050, Povo, Trento, Italy

ⁿFaculty of Science, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065, Japan

^oHarvard-Smithsonian Center for Astrophysics, Cambridge MA 02138 USA

The nearby radio galaxy M87 offers a unique opportunity for exploring the connection between γ -ray production and jet formation at an unprecedented linear resolution. However, the origin and location of the γ -rays in this source is still elusive. Based on previous radio/TeV correlation events, the unresolved jet base (radio core) and the peculiar knot HST-1 at >120 pc from the nucleus are proposed as candidate site(s) of γ -ray production. Here we report our intensive, high-resolution radio monitoring observations of the M87 jet with the VLBI Exploration of Radio Astrometry (VERA) and the European VLBI Network (EVN) from February 2011 to October 2012, together with contemporaneous high-energy γ -ray light curves obtained by the Fermi Large Area Telescope. During this period, an elevated level of the M87 flux is reported at TeV with VERITAS. We detected a remarkable flux increase in the radio core with VERA at 22/43 GHz coincident with the VHE activity. Meanwhile, HST-1 remained quiescent in terms of its flux density and structure in the radio band. These results strongly suggest that the TeV γ -ray activity in 2012 originates in the jet base within 0.03 pc (projected) from the central supermassive black hole.

1. Introduction

The nearby radio galaxy M87 accompanies one of the best studied AGN jets. Its proximity (16.7 Mpc) and brightness have enabled detailed studies of this jet over decades through radio, optical and to X-ray at tens of parsec scale resolutions. Furthermore, the inferred very massive black hole ($M_{\text{BH}} \simeq (3-6) \times 10^9 M_{\odot}$) yields a linear resolution down to 1 milliarcsecond (mas) = 0.08 pc = 140 Schwarzschild radii (R_s) (for $M_{\text{BH}} = 6 \times 10^9 M_{\odot}$), making this source an ideal case to probe the relativistic-jet formation at an unprecedented compact scale with Very-Long-Baseline-Interferometer (VLBI) observations (e.g., Ly et al. 2007; Kovalev et al. 2007; Hada et al. 2011; Asada & Nakamura 2012; Doeleman et al. 2012; Hada et al. 2013). M87 is now widely known to

show γ -ray emission up to the very-high-energy (VHE; $E > 100$ GeV) regime, where this source often exhibits active flaring episodes. The location and the physical processes of such emission have been a matter of debate over the past years, and there are two candidate sites which can be responsible for the VHE γ -ray production. One is a very active knot HST-1 which is located at more than 100 pc from the nucleus (Stawarz et al. 2006; Cheung et al. 2007; Harris et al. 2009). This argument is based on the famous VHE flare event in 2005, where HST-1 underwent a large radio-to-X-ray outburst jointly with a VHE flare. In contrast, the other candidate is the core/jet base, which is very close to the central black hole. This argument is based on the VHE event in 2008, where the core/VHE showed a remarkable correlation in the light curves. There was another VHE event in 2010,

but this is rather elusive. Coincident with the VHE event, Chandra detected an enhanced flux from the X-ray core (Harris et al. 2011; Abramowski et al. 2012), and VLBA observations also suggested a possible increase of the radio core flux (Hada et al. 2012). However, Giroletti et al. (2012) found the emergence of a superluminal component in the HST-1 complex near the epoch of this event, which is reminiscent of the 2005 case.

Recently, the VERITAS Collaboration has reported new VHE γ -ray activity from M87 in early 2012 (Beilicke et al. 2012). While there were no remarkable flares like those in the previous episodes, the VHE flux in 2012 clearly exhibits an elevated state at a level of $\sim 9\sigma$ ($\Phi_{>0.35\text{TeV}} \sim (0.2-0.3) \times 10^{-11} \text{ photons cm}^{-2} \text{ s}^{-1}$) over the consecutive two months from February to March 2012. The observed flux is a factor of ~ 2 brighter than that in the neighboring quiescent periods. Therefore, this event provides another good opportunity for exploring the location of the VHE emission site by jointly using high-resolution instruments.

2. Observations

Here we report a multi-wavelength radio and MeV/GeV study of the M87 jet during this period using the VLBI Exploration Radio Astrometry (VERA, Figure 1), the European VLBI Network (EVN), the Submillimeter Array (SMA) and the Fermi-LAT. We especially focus on the VLBI data in the radio bands; with VERA, we obtained the high-angular-resolution, dense-sampling-interval, phase-referencing data set at 22 and 43 GHz during the VHE activity in 2012: with the supportive EVN monitoring, we obtained a complementary data set at 5 GHz, which enables a high-sensitivity imaging of the M87 jet. A collective set of these radio data allows us to probe the detailed physical status and structural evolutions of M87 by pinpointing the candidate sites of the γ -ray emission i.e., the core and HST-1. For more details regarding the radio data analysis, see Hada et al. (2014).

The LAT data reported here were collected from 2011 February 1 (MJD 55593) to 2012 September 30 (MJD 56200). During this time, the Fermi observatory operated almost entirely in survey mode. The analysis was performed with the **ScienceTools** software package version v9r32p5. The LAT data were extracted within a 10° region of interest centred at the radio location of M87. Only events belonging to the ‘Source’ class were used. The time intervals when the rocking angle of the LAT was greater than 52° were rejected. In addition, a cut on the zenith angle ($< 100^\circ$) was applied to reduce contamination from the Earth limb γ rays, which are produced by cosmic rays interacting with the upper atmosphere. The spectral analysis was performed with the instrument

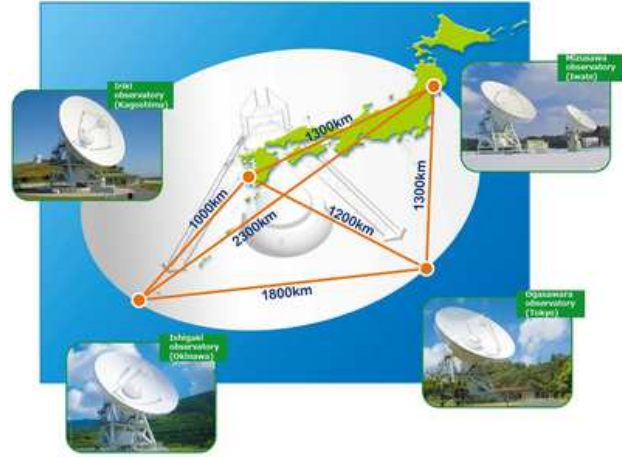


Figure 1: Layout of the VLBI Exploration of Radio Astrometry (VERA).

response functions `P7REP_SOURCE_V15` using an unbinned maximum-likelihood method implemented in the Science tool `gtlike`. A Galactic diffuse emission model and isotropic component, which is the sum of an extragalactic and residual cosmic ray background, were used to model the background. The normalizations of both components in the background model were allowed to vary freely during the spectral fitting.

We evaluated the significance of the γ -ray signal from the sources by means of the maximum-likelihood test statistic $TS = 2\Delta\log(\text{likelihood})$ between models with and without a point source at the position of M87 (Mattox et al. 1996). The source model used in `gtlike` includes all of the point sources from the second Fermi-LAT catalog (2FGL; Nolan et al. 2012) that fall within 15° of the source. The spectra of these sources were parametrized by power-law functions, except for 2FGL J1224.9+2122 (4C 21.35) and 2FGL J1229.1+0202 (3C 273), for which we used a log-parabola as in the 2FGL catalogue. A first maximum-likelihood analysis was performed to remove from the model the sources having $TS < 25$ and/or the predicted number of counts based on the fitted model $N_{pred} < 3$. A second maximum-likelihood analysis was performed on the updated source model. In the fitting procedure, the normalization factors and the photon indices of the sources lying within 10° of M87 were left as free parameters. For the sources located between 10° and 15° , we kept the normalization and the photon index fixed to the values from the 2FGL catalogue.

Integrating over the period from 2011 February 1 to 2012 September 30 (MJD 55593–56200), the fit with a power-law model in the 0.1–100 GeV energy range results in a $TS = 134$, with an integrated average flux of $(2.22 \pm 0.43) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$ and a photon index of $\Gamma = 2.25 \pm 0.10$. Taking into account the detection significance over the whole analysed period,

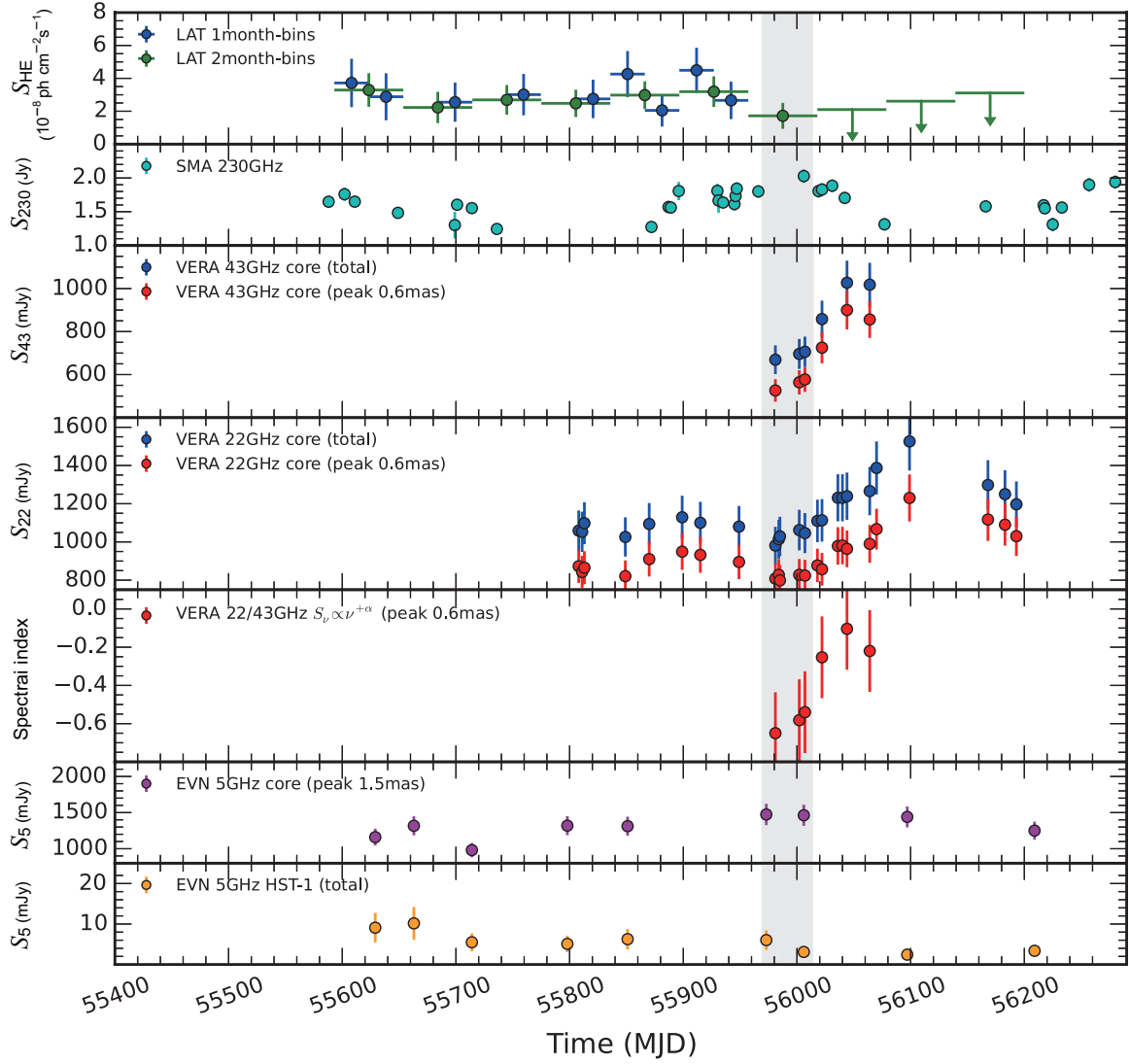


Figure 2: Multi-wavelength light curves of M87 between 2011 February and 2012 December. The vertical shaded area over the plots indicates a period of elevated VHE emission reported by Beilicke et al. (2012).

we produced the γ -ray light curves with 1-month and 2-month time bins. This choice of binning is compatible with those adopted in the previous M87 studies with LAT data (Abdo et al. 2009; Abramowski et al. 2012), and also reasonable for a comparison with the observed month-scale VHE activity in 2012. For each time bin, the spectral parameters for M87 and for all the sources within 10° from it were frozen to the value resulting from the likelihood analysis over the entire period. In the light curve with the 2-month time bins, if $TS < 10$, 2σ upper limits were evaluated, while only bins with $TS > 10$ are selected in the light curve with the 1-month time bins. We describe the results of the LAT light curves in Section 4.2.

Dividing the 1-month bins with higher flux in 5-day sub-bins, the highest flux of $(10.4 \pm 4.8) \times 10^{-8}$ and $(8.6 \pm 3.4) \times 10^{-8}$ $\text{ph cm}^{-2} \text{s}^{-1}$ was detected on 2011 October 12-16 and 2012 January 16-20, respectively

(these sub-bin data also show $TS > 10$). By means of the `gtsrcprob` tool, we estimated that the highest energy photon emitted from M87 (with probability $> 90\%$ of being associated with the source) was observed by LAT on 2011 April 7, at a distance of 0.09° from the source and with an energy of 254.0 GeV, extending into the VHE range.

2.1. Results

In Figure 2 we show a combined set of light curves of M87 from radio to MeV/GeV γ -ray between MJD 55400 and MJD 56280. Thanks to the dense, complementary coverages of VERA and EVN, we revealed the detailed evolutions of the radio light curves for both the core and HST-1. The most remarkable finding in these plots is a strong enhancement of the

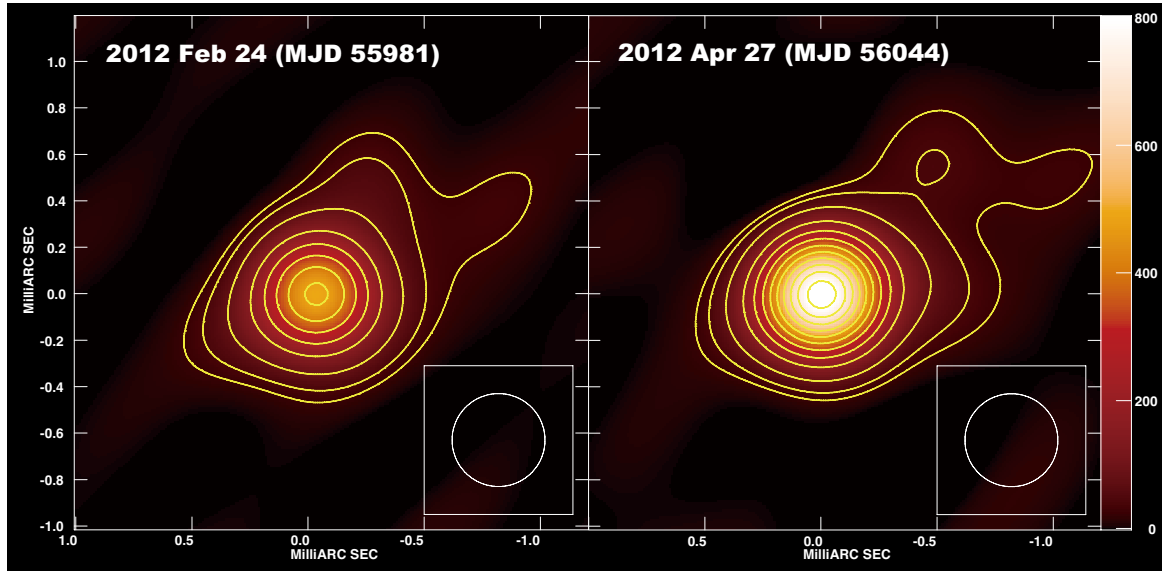


Figure 3: VERA 43 GHz images of the M87 jet during the elevated VHE state in 2012.

radio core flux at VERA 22 and 43 GHz, which occurred coincidentally with the elevated VHE state. At 22 GHz, we further detected a subsequent decay stage of the brightness at the last three epochs. Also at 43 GHz, we detected possible saturation of the flux increase near the last epoch. Meanwhile, the EVN monitoring confirmed a constant decrease of the HST-1 luminosity. Figure 3 describes VERA 43-GHz images during the VHE active period, which indicate the flux enhancement within the central resolution element of 0.4 mas, corresponding to a linear scale of 0.03 pc or $56 R_s$. We also note that the SMA data at 230 GHz also appear to show a local maximum in its light curve during the period of the elevated VHE state.

Another notable finding is a frequency-dependent evolution of the radio core flare. The VERA light curves clearly indicate that the radio core brightens more rapidly with a larger amplitude as frequency increases. At 43 GHz, the flux increased up to $\sim 70\%$ for the subsequent 2 months at an averaged rate of $\sim 35\%$ /month, and afterward the growth seems to be saturated. On the other hand, the core flux at 22-GHz progressively increased up to $\sim 50\%$ for the subsequent 4 months at a slower rate of $\sim 12\%$ /month. At 5 GHz, by contrast, the core remained virtually stable within the adopted error of 10%. This is the first time that such a frequency-dependent nature of the radio flare is clearly confirmed in the M87 jet. We also detected a core-shift between 22 and 43 GHz by using the VERA dual-beam astrometry technique (see Hada et al. 2014), where the amount of the shift was similar to the value obtained in the previous core-shift measurement (Hada et al. 2011).

Regarding the MeV/GeV regime, the LAT light

curves were stable up to February 2012, and we did not find any significant flux enhancement during the period of the VHE activity. After March 2012, however, no significant emission was detected for the subsequent 6 months in the 1- and 2-month binned data, suggesting a change in the HE state after the VHE event. This indicates a decrease in the HE flux (by a factor of ~ 2) after the VHE event, in agreement with the level of decrease observed at VHE in 2012 April-May (Beilicke et al. 2012).

3. Discussion and summary

Following the 2008 episode this is the second time where a VHE event accompanied a remarkable radio flare from the core. Meanwhile, the radio luminosity of the HST-1 region was continuously decreasing, and we did not find any hints of the emergence of new components from HST-1 as seen in 2005 and 2010. These results strongly suggest that the VHE activity in 2012 is associated with the core at the jet base, while HST-1 is an unlikely source. We note that these remarkable flares are very rare also in radio bands (Acciari et al. 2009), so it is unlikely that an observed joint radio/VHE correlation is a chance coincidence, while the low statistics of the LAT light curves still do not allow conclusive results on the HE/VHE connection.

What kinds of mechanisms are responsible for the VHE production in the M87 core? Some of the existing models ascribe the VHE production to extremely compact regions near the central black hole (e.g., Neronov & Aharonian 2007; Lenain et al. 2008; Giannios et al. 2010; Barkov et al. 2012). These models well explain the rapid (a few days) variability observed

in the previous VHE flares in 2005, 2008 and 2010. However as far as we consider the case in 2012, the size of the associated region expected from these models seems to be smaller than that suggested by VLBI and the observed longer timescale of the VHE variability. Indeed, a contemporaneous mm-VLBI observation at 230 GHz during the 2012 event also suggests the possible extended nature for the flaring region ($\gtrsim 0.3$ mas; Akiyama et al. submitted).

Another popular scenario for the M87 VHE production comes from a blazar-type, two-zone emission model where the VHE emission originates in the upstream part of a decelerating jet (Georganopoulos et al. 2005) or in the layer part of the spine-sheath structure (Tavecchio & Ghisellini 2008). However in their steady state models, whether the models can explain the observed simultaneous radio/VHE correlation or not has not been well investigated yet because the emission regions associated with radio and VHE are spatially separated from each other. In this respect, a simple, homogeneous one-zone synchrotron self-Compton jet model examined by Abdo et al. (2009) would be interesting to note since one can in principle accept coincident radio/VHE correlations.

Our multi-frequency radio monitoring additionally revealed a frequency-dependent evolution of the radio light curves for the M87 core. Such a behavior is often explained by the creation of a plasma condensation, which subsequently expands and propagates down the jet under the effect of synchrotron-self-absorption (SSA). The stronger SSA opacity at the jet base causes a delayed brightening at lower frequencies, and the light curve at each frequency reaches its maximum when the newborn component passes through the $\tau_{\text{ssa}}(\nu) \sim 1$ surface (i.e., the radio core at the corresponding frequency). In this context, by jointly using the observed time-lag (Δt_{43-22}) and core-shift ($\Delta r_{\text{proj},43-22}$), we can estimate an apparent speed of the propagating component such that $\beta_{\text{app},43 \rightarrow 22} = \frac{\Delta r_{\text{proj},43-22}}{c \Delta t_{43-22}}$. This results in a speed about $\sim 0.04c - 0.22c$, suggesting that the newborn component is sub-relativistic. This is significantly smaller than the super-luminal features appeared from the core during the previous VHE event in 2008 ($1.1c$; Acciari et al. 2009), where the peak VHE flux is $\gtrsim 5$ times higher than that in 2012. If we assume that propagating shocks or component motions seen in radio observations reflect the bulk velocity flow, this may suggest that the stronger VHE activity is associated with the production of the higher Lorentz factor jet.

We are currently upgrading our M87 monitoring project by using the KVN and VERA Array (KaVA; Niinuma et al. 2014), which dramatically improves jet imaging capability thanks to the increase of the number of telescopes/baselines plus the addition of shorter baselines. This will enable us to constrain the jet kinematics and radio/VHE connection more precisely.

tics and radio/VHE connection more precisely.

Acknowledgments

The VERA is operated by Mizusawa VLBI Observatory, a branch of National Astronomical Observatory of Japan. e-VLBI research infrastructure in Europe is supported by the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. RI-261525 NEXPReS. The European VLBI Network is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils. The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

The Fermi LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l'Energie Atomique and the Centre National de la Recherche Scientifique Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK) and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the Swedish National Space Board in Sweden. Additional support for science analysis during the operations phase is gratefully acknowledged from the Istituto Nazionale di Astrofisica in Italy and the Centre National d'Etudes Spatiales in France.

References

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, *ApJ*, 707, 55
- Abramowski, A., Acero, F., Aharonian, F., et al. 2012, *ApJ*, 746, 151
- Acciari, V. A., Aliu, E., Arlen, T., et al. 2009, *Science*, 325, 444
- Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, *Science*, 314, 1424
- Asada, K. & Nakamura, M. 2012, *ApJ*, 745, L28
- Barkov, M. V., Bosch-Ramon, V., & Aharonian, F. A. 2012, *ApJ*, 755, 170

- Beilicke, M., & VERITAS Collaboration 2012, arXiv:1210.7830
- Cheung, C. C., Harris, D. E., & Stawarz, L. 2007, ApJ, 663, L65
- Doeleman, S. S., Fish, V. L., Schenck, D. E., et al. 2012, Science, 338, 355
- Georganopoulos, M., Perlman, E. S., & Kazanas, D. 2005, ApJ, 634, L33
- Giannios, D., Uzdensky, D. A., & Begelman, M. C. 2010, MNRAS, 402, 1649
- Giroletti, M., Hada, K., Giovannini, G., et al. 2012, A&A, 538, L10
- Hada, K., Doi, A., Kino, M., et al. 2011, Nature, 477, 185
- Hada, K., Kino, M., Nagai, H., et al. 2012, ApJ, 760, 52
- Hada, K., Kino, M., Doi, A., et al. 2013, ApJ, 775, 70
- Hada, K., Giroletti, M., Kino, M., et al. 2014, ApJ, 788, 165
- Harris, D. E., Cheung, C. C., Stawarz, L., et al. 2009, ApJ, 699, 305
- Harris, D. E., Massaro, F., Cheung, C. C., et al. 2011, ApJ, 743, 177
- Kovalev, Y. Y., Lister, M. L., Homan, D. C., & Kellermann, K. I. 2007, ApJ, 668, L27
- Lenain, J.-P., Boisson, C., Sol, H., & Katarzyński, K. 2008, A&A, 478, 111
- Ly, C., Walker, R. C., & Junor, W. 2007, ApJ, 660, 200
- Mattox, J. R., Bertsch, D. L., Chiang, J., et al. 1996, ApJ, 461, 396
- Neronov, A., & Aharonian, F. A. 2007, ApJ, 671, 85
- Niinuma, K., Lee, S.-S., Kino, M., et al. 2014, PASJ, 66, 103
- Nolan, P., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
- Stawarz, L., Aharonian, F., Kataoka, J., et al. 2006, MNRAS, 370, 981
- Tavecchio, F., & Ghisellini, G. 2008, MNRAS, 385, L98